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A review of prefabricated biogas digesters in China

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ABSTRACT

China plays a leading role in the worldwide development and dissemination of household-based biogas technology. Since the 1980s, China has developed many types of commercialized or half-commercialized prefabricated biogas digesters (PBDs), which are categorized into three: glass fiber-reinforced plastic digesters, plastic soft digesters, and plastic hard digesters. This paper summarizes the development of PBDs in China, including their key characteristics, manufacturing process, advantages and disadvantages, cost analysis, marketing, and future prospects. Furthermore, the paper highlights and analyzes potential constraints in the promotion of these types of digesters; examples of these constraints include incomplete standardization systems, insufficient demonstration projects, low-quality digesters, and missing authorizations from the inspection department. A preferential policy should be formulated for the prefabricated digester industry. Specifically, the standardization system should be improved, technological innovations should be encouraged, self-regulation of the industry should be intensified, demonstration projects should be implemented, and follow-up services should be improved. PBD technologies can potentially be applied with great reliability and high efficiency not only in China but also in other countries.

Contents

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1. Introduction

In 2009, China overtook the United States as the world's largest energy user [1]. The consumption of fossil fuels brings about serious pollution and causes global warming. Therefore, reducing the dependency on fossil fuels through the development of sustainable energy sources is a prerequisite for the sustainable economic development of China. In the Medium- and Long-term Development Program for Renewable Energy, China set the renewable energy target to account for 10% of the total energy consumption by 2010 and for 15% of the total energy consumption by 2020 [2]. Renewable energy in 2009 already accounted for 9.9% of the total energy consumption [3]. Renewable energy includes wind power, solar energy, hydroenergy, and bioenergy. As one kind of bioenergy, biogas is a key energy carrier from biomass feedstock after anaerobic digestion. Biogas technology offers a unique set of benefits: it can improve the health of users, promote agricultural structural adjustment, increase rural income, enhance the ecology of rural areas, optimize the rural energy consumption structure, and improve the quality of both rural life and agricultural products [4–8]. The construction of biogas plant for rural households is a key program of the New Rural Communities Construction for renewable energy supply in China [9]; this program contributes to reduce the problem of global warming [10].

China plays a leading role in the worldwide development and dissemination of household-based biogas technology [11,12]. At the end of 2011, 41.68 million households were using biogas, including centralized biogas supply; given the 34.7% rate of popularization among suitable households, 160 million people in rural China were benefitting from this renewable energy during this period [13]. However, the performance of household digesters is not at the optimum level. Well-operating household digesters reportedly accounted for less than 60% of the total number in 2006 [14]. Reasons for this condition are multifold. (1) Rural biogas efficiency and profits are relatively low, and fatal accidents occur during cleaning of the digester. (2) Given the low income from livestock breeding, farmers give up and move to cities to find well-paying jobs. (3) Natural disasters such as earthquakes and floods damage digesters built with traditional materials such as bricks or concrete, (4) Farmers managing household digesters do not have access to follow-up financial support. The lack of assistance leads to the poor maintenance and operation of biogas plants [11,15,16].

Most household biogas digesters in rural China are constructed onsite and built from bricks and concrete. The poor construction of digesters may cause leakages after a short period of operation. Once broken, digesters cannot be repaired easily for normal operation. The traditional construction materials are heavy, and transportation is a big problem for remote and mountain areas. The construction is also time consuming, often stretching to several months [17].

To overcome the weakness of brick and concrete household digesters, many kinds of alternative materials have been tested and used as replacement. Fiber-reinforced plastic, modified plastic, and other new materials have gradually found their way into the construction of biogas digesters and systems [11]. In contrast to onsite-constructed brick and concrete digesters, a prefabricated biogas digester (PBD) is produced offsite using materials with special physical properties. In China, prefabricated digesters are often called "commercialized digesters"; as new production materials, processes, and techniques are usually adopted, these digesters are also called the "three new digesters." The China Association of Rural Energy Industry (CAREI) predicted that the application of commercial biogas digesters should be corollary to biogas industry development to keep pace with modern technologies [18]. Based on the new emerging market, this paper gives a review of PBDs in China, including their key characteristics, materials applied, economy, marketing, and future prospects. The paper also summarizes existing challenges and analyzes the countermeasures required to establish a sound industry.

2. Development of PBDs in China

2.1. History of PBDs

Since the 1980s, China has developed many kinds of commercialized or half-commercialized household biogas digesters, such as polyethylene (PE) digesters, semi-hard plastic digesters, iron digesters, glass-reinforced plastic or fiber-reinforced plastic (FRP) digesters, glass fiber-reinforced composite digesters, acrylonitrile

Table 1
Chronology of PBD development in China [14,18,68].

Year	Related activity and description
1980s	All kinds of PBDs appeared and were put into experimental use.
1986	The earliest patent involved in FRP digester in China was recorded, called "bottom-discharge digester".
1992	The earliest patent involved in assembled digester in China was recorded, called "prefabricated assembled digester".
2000	The first commercial FRP digester was developed.
2004	The first commercial PS digester was developed.
2005	Sheet molding compound (SMC) production of FRP digester first appeared to replace hand lay-up made FRP digester.
2006	The earliest patent involved in PS digester in China was recorded, named "new-type soft digester".
2009	The first PBDs standard NY/T 1699–2009 was released by Ministry of Agriculture (MoA), aiming at FRP digester.
Present	More than 100 enterprises works on the manufacture of PBDs in China with a total annual production of more than 2,500,000 sets of PBDs.

butadiene styrene (ABC) digesters, ferro-/bamboo cement digesters, and wire mesh cement prefabricated digesters [19,20]. Since 2000, PBDs have entered the real commercial stage, and a number of manufacturers have emerged in the industrial scene. The chronological development of PBDs in China is shown in Table 1.

2.2. PBD types

Digesters today have no exact classification. In the CAREI report, prefabricated or commercial digesters are classified as FRP digesters, plastic soft (PS) digesters, and plastic hard (PH) digesters. FRP digesters are representative of PBDs, as they entered the market at the beginning of the development. Their raw materials are unsaturated polyester resin and glass fiber cloth. PS digesters are also called bag digesters in some countries because they look like big soft bags. Materials applied include soft polyvinyl chloride (PVC), red mud, polymethyl methacrylate, low-density PE, PE, and polypropylene (PP). PH digesters are normally hard digesters. In contrast to soft digesters, PH digesters are made out of hard PVC, ABS, PE, PP, high-density polyethylene (HDPE), and linear low-density PE. The plastic properties of the materials that are normally used to produce PBDs are shown in Table 2 [21]. A comparison of the three categories is displayed in Table 3.

2.2.1. FRP digester

Since the development of FRP digesters between 2000 and 2010, about 200,000 FRP digesters have been installed. In 2005, the National Development and Reform Commission (NDRC), the Ministry of Science and Technology, and the former State Environmental Protection Administration (now the Ministry of Environmental Protection) co-released the *National Encouraged Technology on Resource Conservation, Comprehensive Utilization, and Environmental Protection*. It explicitly declared that traditional brick-/concrete-based digesters do not meet the requirements for commercialization and large-scale implementation, whereas FRP digesters are promising technologies for dissemination. The standard *NY/T 1699–2009 Technical Specifications for Household Anaerobic Digesters of Fiberglass Reinforced Plastic* establishes the four processes for manufacturing FRP digesters: hand lay-up, sheet molding compound (SMC), resin transfer molding, and filament winding. The SMC process requires a 3000-ton heavy press machine and a 100-ton heavy mold; prefabricated SMC sheets are used as raw material under a pressure of 100 kg/cm^2 and a temperature of 140 °C. A half digester is produced every 6–8 min. However, the SMC process requires an expensive investment of at least 10 million CNY (1 USD=6.207 CNY, 30/11/2012, Bank of China). Therefore, a new impulse mold pressing technology has been promoted under the National Science and Technology Innovation Fund [22].

Two types of FRP digesters are promoted: a top-half FRP digester consisting of a top half made of FRP and a bottom half made of concrete (see Fig. 1) and a complete FRP (see Fig. 2). The installation of a complete FRP digester is much easier than that of a top-half FRP digester. However, top-half FRP digesters have two advantages over complete FRP digesters: (1) they incur 30% less cost, and (2) they can overcome the shortcoming of complete FRP digesters, which tend to sink if the groundwork is not strong enough [23,24]. A cost analysis between onsite-constructed digester (OCD) and top-half FRP digester is given in Table 4. The price of a top-half FRP digester is somewhat higher than that of an OCD. At present, the most popular FRP digester resembles a "kettle". Its raw material comprises unsaturated polyester, gel-coated resin, chopped strand mat, and high-quality glass fiber cloth. The inner surface of the digester is painted with gel-coated resin to ensure tightness. The digester body is normally divided into top-half and bottom-half parts and pre-installed with a gas outlet pipe, an inlet hole, an outlet hole, and a hydraulic chamber. Volumes of FRP digesters range between 2.5 and 10 m^3, but the most common volumes of FRP digesters are 4, 6, and 8 m^3 [25–27]. The thickness of FRP digesters range from 6 mm to 8 mm, tensile strength can reach 93.5 MPa, and flexural strength can reach 109 MPa. The digesters can be piled up upon release from the factory; an 8 m^3 truck compartment can load 40 digesters [28].

The development of FRP digesters is related to the development in fermentation technology. An FRP digester with a rotational flow has been introduced and tested; results show an increase in biogas yield by 30.6% compared with conventional hydraulic digesters as well as an increase in methane content by 4–12% [29,30]. Further research has revealed that the methane content of biogas from FRP

Table 2
Related plastic properties for PBDs.

Plastic material	Water absorption/ 24 h	Tensile strength/ MPa	Recovery	Combustibility	Price[a] /CNY[b] per ton
UP	< 1	700	Hard	Hard	11500
PP	< 0.2	25–40	Easy	Sustained combustion	10750
PE	< 0.05	8–30	Easy	Sustained combustion	9800
ABS	0.8–1.6	45–65	Easy	Sustained combustion	14500
PVC	0.1–0.8	45–80	Easy	Self-quenching	6100

[a] The price is referred to average quotation from China's chemical industry, June of 2012.
[b] 1 USD=6.207 CNY, 30/11/2012, Bank of China.

Table 3
Comparison of PBDs [21,69] (volume=8 m^3).

Category	Main materials	Construction cycle /Man-hours	Price[a]/ CNY[b]	Process
FRP digester	UP+glass fiber cloth	Hand-made: 30 Factory production: 64	1800–2800	Hand lay-up Sheet molding compound (SMC) Resin transfer molding (RTM) Filament winding (FW)
PH digester	PP	24	1700–2400	Injection molding
	PE	24	1600–2200	Rotational molding
	PP+PE	24	1800–2400	Injection/rotational molding
	ABS	24	2500–3200	Stamping/blow molding/ squeezing
	PVC	24	1600–2000	Welding assembly
PS digester	PVC+red mud	48	1500–1800	High frequency thermal welding
	PVC	48	1600–2000	Welding
	PE+red mud	48	1600–1800	Thermal welding

[a] Personal communication with CAREI.
[b] 1 USD=6.207 CNY, 30/11/2012, Bank of China.

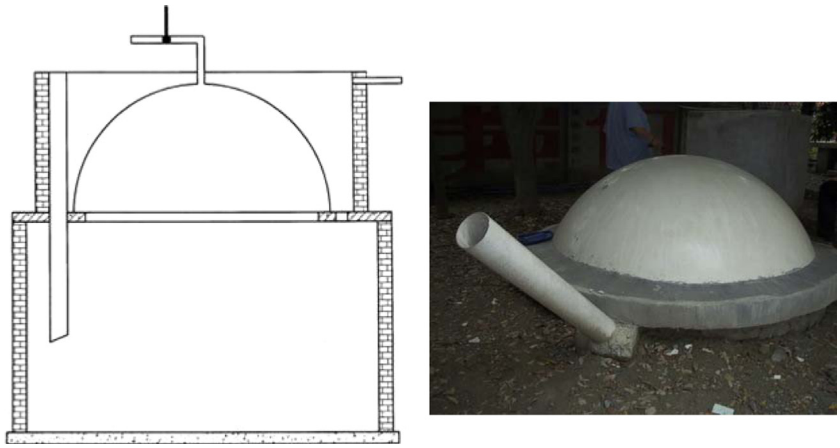

Fig. 1. Top-half FRP digester.

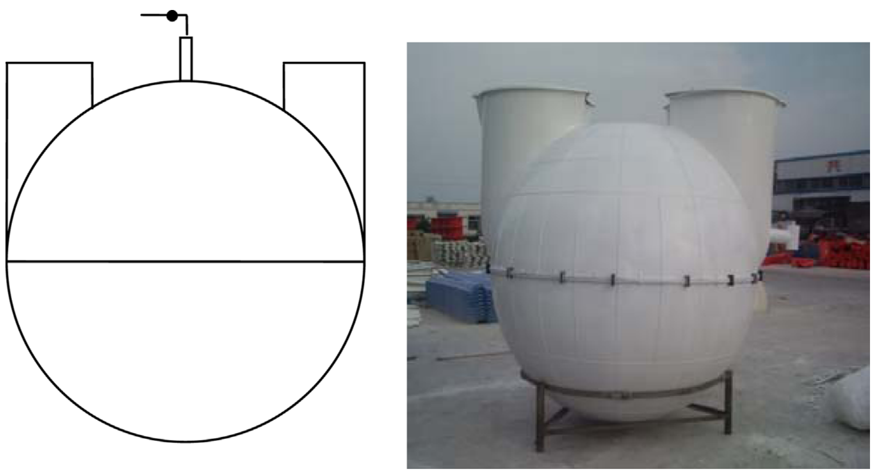

Fig. 2. Complete FRP digester.

Table 4
Cost comparison between OCD and top-half FRP digester[a] (volume = 8 m^3).

Item	OCD				Half FRP digester			
	Quantity	Unit	Price/CNY[b]	Sum	Quantity	Unit	Price/CNY	Sum
Total				2743				3075
Material fee				1493				2005
Cement	1	ton	450	450	0.6	ton	450	270
Medium sand	3	m^3	80	240	2.5	m^3	80	200
Stone	3	m^3	80	240	2.5	m^3	80	200
Brick	1200	piece	0.35	420	700	piece	0.35	245
Steel bar	20	kg	4	80	10	kg	4	40
Sealing agent	2	kg	6.5	13	0	kg	6.5	0
Prefabricated Inlet pipe	1	piece	35	35	1	piece	35	35
Prefabricated Slurry pipe	1	piece	15	15	1	piece	15	15
					1	set	1000	1000
Construction fee				1250				1070
Soil digging	10	CNY/m^3	35	350	10	CNY/m^3	35	350
Technician fee	5	working day	80	400	4	working day	80	320
Assistance fee	10	working day	50	500	8	working day	50	400

[a] Data are from Sichuan Rural Energy Office, 2011. <Unpublished results>.
[b] 1 USD = 6.207 CNY, 30/11/2012, Bank of China.

digesters is 15.3% higher than that from concrete digesters [26]. An FRP digester with integrated solar heating has also been designed and tested, resulting in good biogas yields even in winter [31]. An innovative rotary stirring technology has been installed in an FRP digester, thereby resulting in a threefold increase in biogas yield compared with digesters without stirring technology [32].

2.2.2. PS digesters

A PS digester is characterized by its soft material and convenient packing; it could be laid in a concrete structure, a chamber, or directly in a pit. The most popular materials for PS digesters are PVC, PE, and red mud plastic (RMP). In the 1980s, some experiments were carried out with RMP [33,34]. The impact of RMP on

microorganisms during fermentation has been tested and showed no negative effect [35]. A red mud floating cover has also been adopted, resulting in an increase in biogas yield by up to 30–50% [36]. Parts of digesters can also be replaced with PVC material. For example, only the cover is made of soft material; the other parts are still concrete. A new type of biogas system composed of a solar heating system, a PVC soft digester, and a circulating heat transfer system has been designed and tested. The system is suitable for locations with a marked winter season [37]. PE was used in the beginning of the prefabrication industry, but it has now been replaced by PVC and RMP. At present, RMP (also called "red mud membrane") can also be used as cover for digesters or as biogas storage at large-scale biogas plants. It is also helpful in the overhauling of biogas digesters after years of operation [38].

As a new technology, PS digesters bring new concepts and vitality to the Chinese biogas industry. Despite the wide range of opportunities for PS digesters, several challenges must still be overcome; these challenges include the lack of basic technical standards, inconsistent product quality, and lack of comprehensive and standard specifications. In 2011, CAREI established a specialist group for PS digesters to promote industrial technical standards, to jointly develop high-end products, and to meet client requirements, thereby enhancing the smooth development of the Chinese biogas industry [39].

2.2.3. PH digesters

PH digesters were developed and tested in the 1980s [40]. Generally, a PH digester is made of hard materials excluding FRP. The materials include hard PVC, ABS (Engineering Plastics), HDPE, and modified plastics. This kind of digester is composed of several pieces of mechanically pressed sheets and can be easily assembled onsite. The technology is characterized by high production efficiency and low labor intensity [41]. Flat-sphere improved plastic digesters have been tested, and the results predict excellent prospects [42,43]. A modified plastic digester has also been tested and promoted in rural areas with satisfying results [14]. Meanwhile, a solar heated digester has been developed for and in cold areas, thus overcoming the bottleneck in the promotion of brick/concrete digesters because biogas production is reduced significantly in winter. This hard PVC digester has received positive consumer feedback [44]. An automatic back-flow scum-breaking digester has been built with hard PVC plastics [45]. It has the following properties: high strength, anti-aging, corrosion resistant, no leakage, good tightness, lightweight and convenient transportation, fast and easy construction and installation, and long service life of more than 30 years. It can be installed in any kind of soil and under any environmental condition. Research has been conducted to replace the outlet chamber channel with a hard PVC pipe; such replacement has been proven feasible, especially in locations where digging a pit is a challenge [46].

2.2.4. Other types

In the early phase of the industrial development of PBDs, the ferro-cement type of construction was applied either as a self-supporting shell or as earth-pit lining. The vessel form was usually cylindrical. Plants under 6 m^3 were prefabricated. As in the case of a fixed-dome plant, the ferro-cement gasholder requires special sealing measures; proven reliability is provided with cement-on-aluminum foil. Ferro-cement can be replaced by bamboo cement.

With the expansion of the market, the portable and onsite-assembled digester was invented. This digester is a dismountable unit that is mainly used to treat green and kitchen waste. A typical portable and assembled digester is shown in Fig. 3. With the diversification of feedstock for anaerobic digestion and with the shortage of animal manure in rural areas, portable and assembled digesters are expected to be a promising technological approach for the treatment of any organic waste [47].

2.3. Key characteristics of PBDs

PBDs were invented when biogas technology implementers realized the disadvantages of onsite-constructed brick- and concrete-based digesters. An obvious advantage of PBDs over masonry digesters is the permanent quality control at the factory. PBDs could bear enough mechanical strength with good air tightness and long service life. They normally have a good insulation effect to maintain permanently stable internal temperature. PBDs are light and can thus be easily transported. No long construction periods are required because they are produced offsite in advance and could be stored until used. A qualitative comparison among PBDs and OCDs is presented in Table 5. Generally, PBDs cost higher than OCDs [48,49]; FRP digesters are more expensive than PH digesters and PS digesters. PBDs are also endowed with further disadvantages, as elaborated in Table 6, which displays the merits and demerits of PBDs.

Compared with OCDs, PBDs are suitable for the following places:

1. Sites where the ground water level is high, as in coastal areas where constructing onsite brick, stone, concrete, or molded digesters is difficult; and where the quality of digester construction cannot be controlled while guaranteeing gas and water tightness
2. Sites located in remote and/or mountain areas, where providing and transporting conventional construction materials are difficult

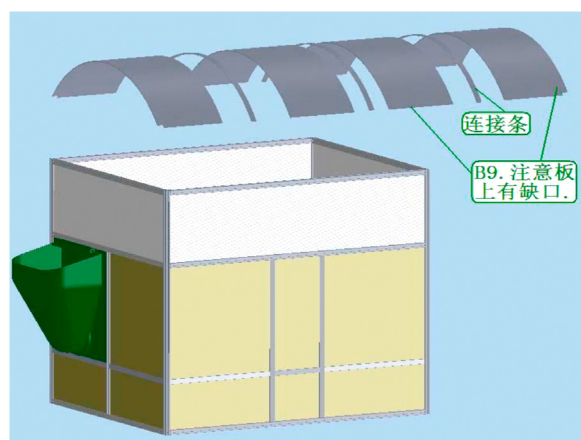

Fig. 3. A typical portable and assembled digester.

Table 5
Qualitative comparison among PBDs and OCDs[a].

Item	FRP digester	PS digester	PH digester	Masonry digester
Cost	High	Small	Normal	Normal
Construction period	Short	Short	Short	Very long
Transportation	Easy	Very easy	Easy	Impossible
Maintenance	Almost no	Almost no	Almost no	Frequent
Mechanical property	High	Weak	High	High
Service life	Long	Short	Long	Normal
Water adsorption	Low	Low	Low	High
Tightness	Good	Normal	Good	Normal

[a] Summarized by authors after personal communication with Chengdu Hongqi Industrial Co., Ltd., Chengdu Datangren Biogas Technology Development Co., Ltd., Anqing Chonglang Energy Science and Technology Co., Ltd., 2012.

Table 6
Advantages and disadvantages of PBDs [19,28,70–72].

Category	Advantages	Disadvantages
FRP digester	Mature production process; Uniform quality under industrial standard; Good air-tightness; High gas production; Fast heating up	High cost of raw materials and fluctuations in prices; Floating where high underground water level persists; Digester shape needs to be improved; Secondary pollution after breakdown
PS digester	Low production cost; Good air-tightness; Fast heating up; Easy transportation	Easily pierced by sharp items or animal tooth; Aging of material; Extra pump required to transport biogas; Inconvenient feeding and discharge
PH digester	Low production cost; Good air-tightness; Fast heating up	Easily damaged by blunt so stress intensity should be improved; Floating where high underground water level persists; Material is easily oxidized when it is exposed to air or buried in the earth.

Table 7
Production and sale capacity of PBD producers in China [63].

	Production capacity/year	Sale volumes 2010	Sale volumes 2008–2010	Expected sales by 2011	Annual production in CNY[a]	Number of employee
FRP digester	500,000 sets	210,000 sets	440,000 sets	280,000 sets	470 million	1340
PS digester	1,400,000 sets	140,000 sets	330,000 sets	270,000 sets	220 million	1686
PH digester	600,000 sets	70,000 sets	100,000 sets	100,000 sets	150 million	1160
Total	2,500,000 sets	420,000 sets	870,000 sets	650,000 sets	840 million	4186

[a] 1 USD=6.207 CNY, 30/11/2012, Bank of China.

3. Sites with inadequate conventional construction materials and specialized labor force, thus resulting in increased construction cost or extended program overheads because of repetitions in training sessions
4. Sites where residential areas are modified and rebuilt as a result of rural reconstruction and land reform measures or inheritance, thus affecting the permanent site locations of conventional digesters.

2.4. Marketing

Unlike OCDs, PBDs are few in number, but their potential market is huge. Most manufacturers established their businesses after 2000. Currently, China has 100 PBD manufacturers, that is, at least one PBD manufacturer in nearly every province. About 20 key enterprises manage trans-provincial businesses and even international businesses that particularly aim for the African market under governmental assistance projects. Other Southeast Asian countries like Myanmar, Vietnam, Bangladesh, and Cambodia also import PBDs from China and have started testing them in their respective countries to explore their domestic markets [50]. The CAREI carried out an investigation on PBD marketing in 2011, covering 29 key enterprises in China; an overview is given in Table 7.

3. Household biogas digester technologies across the world

Biogas digesters from other countries are different from those used in China to some extent. The structure, operational principles, performance, and application of these digesters also vary from region to region and from country to country. In terms of digester structure, three types of digesters are available (Fig. 4): (1) fixed dome digesters or hydraulic digesters, which are most common in Nepal, Cambodia, Vietnam, Pakistan, Bangladesh, and Africa; (2) floating cover digesters, which are commonly seen in India and Africa; (3) balloon or tube digesters, which can be found in Southeast Asian countries such as Vietnam and Myanmar [51,52]. All three types of digesters can be found in China, but fixed dome digesters remain dominant.

Some countries in Asia, such as Nepal, Bangladesh, Vietnam, Cambodia, Lao PDR, Pakistan, Indonesia, and Bhutan, have launched national biogas programs. Some countries in the African region, such as Lesotho, Rwanda, Burundi, Burkina Faso, Ethiopia, Tanzania, Uganda, Kenya, and Senegal, employ household biogas systems [53,54]; some of these countries are members of the Africa Biogas Partnership Programme [55]. The experiences and lessons learned from Asia and Africa are being applied in Latin America, where biogas programs have already been established in Peru, Bolivia, Colombia, and Guatemala since the 1980s. With new lessons learned, Nicaragua conducted a feasibility study in 2010 and initiated a new national biogas program in 2012. Bolivia also followed such programs, and other countries are also assessing their potential [56–58].

The most common digester model under national biogas programs is the fixed dome digester or the so-called hydraulic digester. The operational principles of these digesters are similar despite their different structures. Fig. 5 shows typical biogas digesters being promoted in some countries. With regard to the digester design, the original Chinese fixed-dome design was initially implemented. The GGC 2047 design, which was developed in Nepal, was then promoted in some African countries (e.g., Ethiopia, Rwanda [59]) under the Biogas Partnership Programme. These digester designs were later adapted as necessary based on the conditions of the respective countries (i.e., CARMATEC design in Tanzania and Uganda, LUPO/TED design in Ethiopia and Lesotho) [60].

PBDs can be processed and produced with different materials based on the different types of biogas digesters. PBDs are also being tested in some countries, with most of the initial models introduced from China and some developed locally; for example, PBDs in South Africa are based on commercial water tanks [61]. Compared with

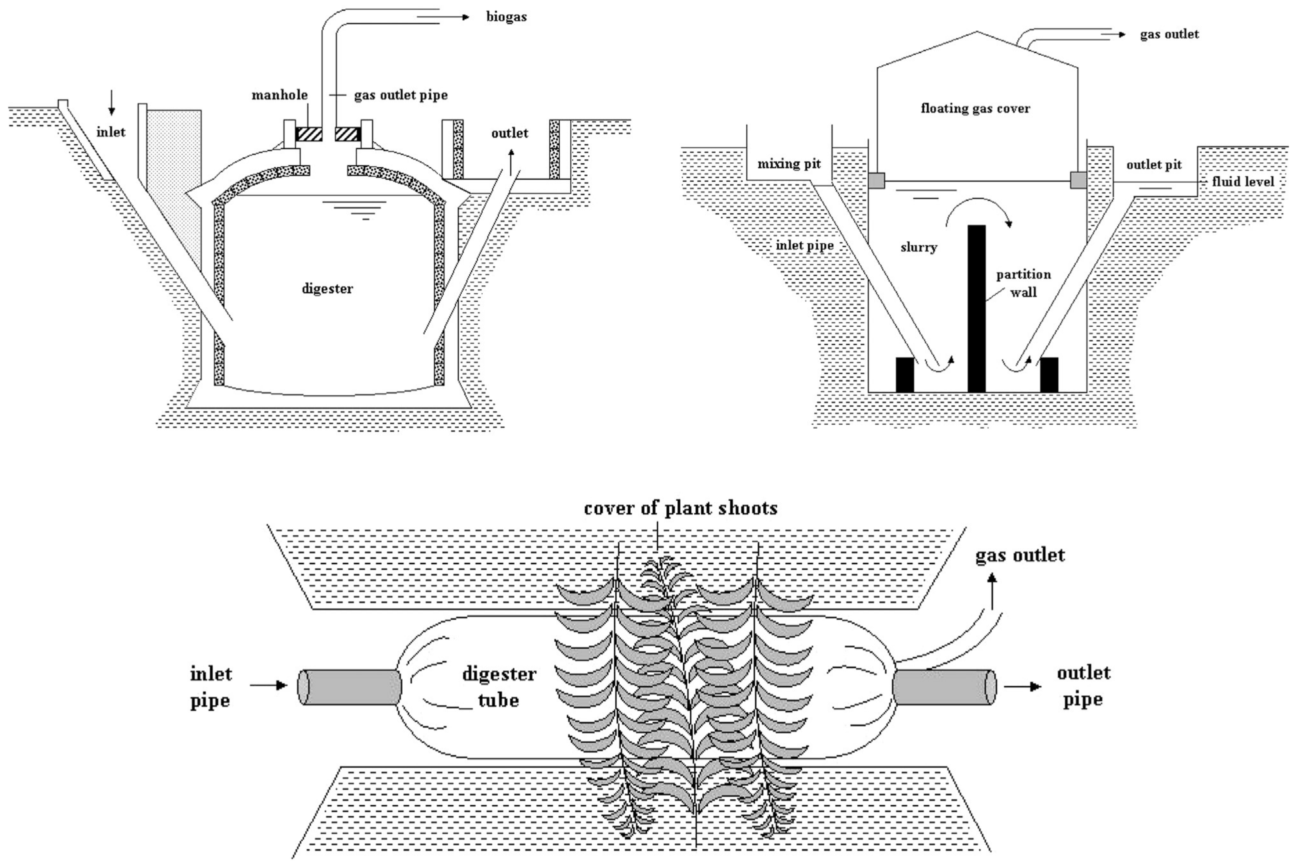

Fig. 4. Three major types of digesters in the developing world. Top left: fixed dome digester. Top right: floating cover digester. Below: balloon or tube digester.

Chinese PBDs, the process technology is relatively laggard while the handmade process is normally adopted. Most of the hard-structured PBDs worldwide that are based on the hydraulic principle are composed of a digester body with pressure compensation volume for the inside gas storage space in the outlet and the inlet. Bag digesters (ball types and sausage types) with flexible bodies have been used in Colombia, Venezuela, Barbados, and Cuba for the past 30 years. The first bag digesters were made of RMP or red mud PVC biogas digester bags manufactured in Taiwan. In 1993, Vietnam began to develop flexible, sausage-shaped biogas digesters or multi-layer, low-cost plastic sausages with locally available green house plastic based on the experiences of Cuba and with support of the Food and Agriculture Organization.

4. Barriers to and challenges in the development of PBDs in China

In recent years, China's biogas industry has developed rapidly, and the PBD industry has expanded gradually with government support at all levels. However, the development of the PBD industry in China remains unconsolidated and inevitably faces barriers and challenges.

4.1. Inappropriate standardization system and insufficient policy support

The world-renowned standardization system for the Chinese biogas industry includes 35 criteria and 4 categories (basic standards, product standards, technical specifications, and construction specifications) [62]. However, no industrial standard is in place for PS digesters and any other type of PBDs, except for FRP digesters. One reason is their non-inclusion in the governmental agenda for biogas technology promotion. Local governments and farmers therefore lack a basis for their judgment of PBDs. In March 2009, the Ministry of Agriculture (MoA) released the standard *NY/T 1699–2009* for FRP digesters. However, implementing this regulation is difficult.

Meanwhile, the MoA, local governments, and related departments are very careful in selecting products under government loan. In 2003, the MoA and NDRC issued a *National Debt Management Method for Rural Biogas Construction*. However, the regulation does not clearly indicate whether the PBD industry can obtain a subsidy. This drawback definitely limits the development of the PBD industry [17].

4.2. Inadequate number of demonstration projects

At the initial phase of dissemination, a demonstration project must inform government and rural energy offices about the advantages of PBDs. Public comprehension must then be increased to improve the acceptance of the product in the market. As government and sector stakeholders have limited knowledge of PBDs, little emphasis is given to the development of the PBD industry, thus resulting in an inadequate number of pilot projects that implement PBDs. Consequently, demonstration projects for reference are lacking.

4.3. Lack of industrial specifications and impact of inferior products

As no effective guidance is given to the market, the quality of PBDs varies greatly. Some enterprises adopt inferior materials or the jerry-built method for manufacturing to reduce production cost. In addition, the techniques applied to match the competition leads to damage of corporate image and disruption of market order [63].

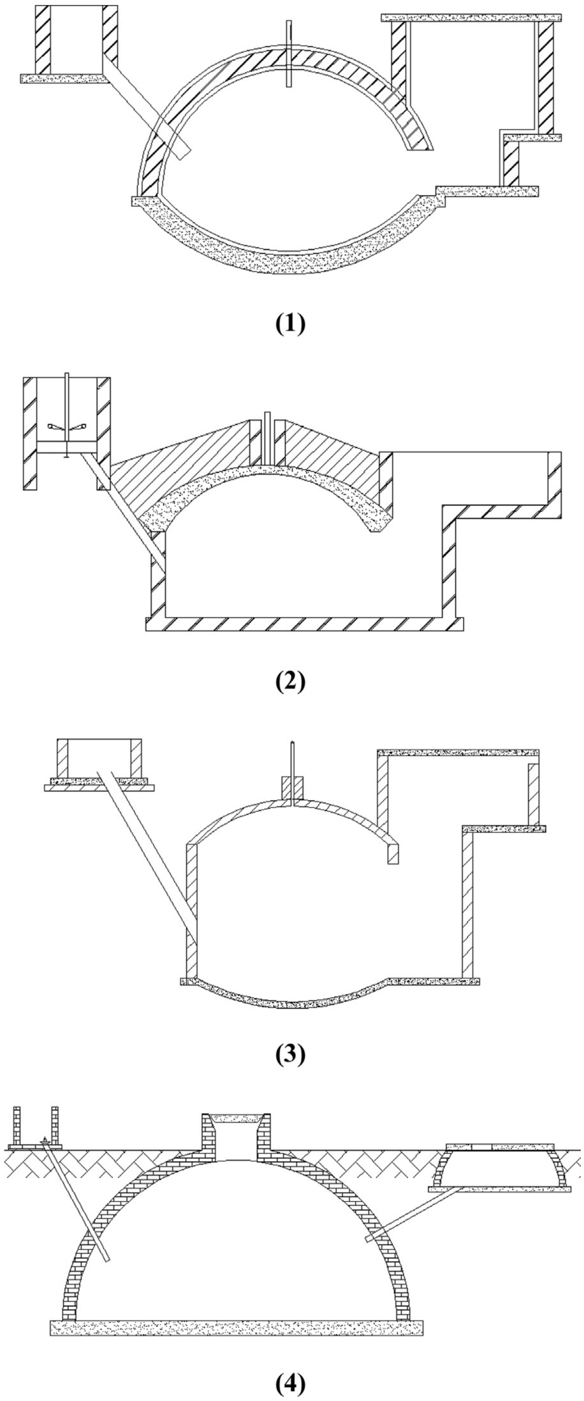

Fig. 5. Typical fixed dome digesters in India (1), Nepal (2), Bangladesh (3) and VietNam (4).

Products of bad quality have already disappointed users, resulting in a loss of confidence in digesters. Although high-quality products are available in the market, regular users cannot distinguish between good and bad quality. For instance, FRP digesters made of inorganic materials (i.e., MgO and $MgCl_2$) with high water-absorption capacity were once introduced in the market. Given these characteristics, these digesters were of poor waterproofing quality. Nevertheless, these digesters attracted several enterprises because of the low cost; however, they broke down quickly in practice. The users mistook these FRP digesters as the real ones and eventually lost confidence in the appropriateness of FRP for biogas technology. This case seriously affected the reputation and promotion of FRP digesters.

4.4. Lagging authorization by inspection department

Products that cannot provide corresponding technical appraisement and testing certificates are restricted in their promotion. The standard *NY/T 1699–2009* was released by the MoA in 2009. However, the Quality Supervision, Inspection, and Test Center for Biogas Products and Equipment of the MoA has not yet been authorized for certification as of mid-2013. Therefore, the center can release test results but cannot make any qualified conclusions. Local energy departments generally do not approve test reports without qualified conclusions.

5. Recommendations for the PBD industry in China

To overcome the aforementioned problems of the PBD industry in China and to benefit from available opportunities by targeting the sustainable development of this industrial sector, several actions for the feasible development of China's PBD industry are proposed.

5.1. Increase policy support and create preferential policy

The dominant factor in Chinese biogas project development is policy guidance [64]. Policies are mainly implemented by legal means, whereas laws and regulations are created under certain policies [65]. The state should highlight the support force and enlarge the preferential policy. Financial subsidies should be properly supplied to PBDs in the same way as subsidies are provided for OCDs. The government could invest in the research and development of products for PBD manufacturers. At present, a considerable amount of funds are allocated to large-scale biogas projects. Nevertheless, the investment in R&D for the PBD industry is low, thus restricting the initiatives of PBD manufacturers.

The subsidy system should create incentives to motivate the manufacturers to develop quality products. From input (initial investment) to output (end product), detailed subsidies can be assigned to complete the subsidy system. Mechanisms for subsidies should also be improved; rewards could replace subsidies to stimulate the acceptance of enterprises and users. The proper allocation of all subsidies must be ensured.

5.2. Perfect the industrial standardization system and strengthen Public awareness of standards

Only one national PBD standard aimed at FRP digesters exists. Other standards have also established for testing FRP [54]. Standards for PS and PH digesters should be formulated immediately to keep pace with the rapidly growing PBD industry. Related standards for testing methods should also be established. Most of the new PBDs are still in the pilot and exploration stages, during which the formulation and popularization of standards are important to promote the sound development of PBDs. Concerned authorities at different levels should guide the normalization of PBDs and capacitate relevant technical staff.

5.3. Improve R&D funds and promote technological innovation

To promote technological progress, R&D investment for new technology should be increased, and innovation systems that are enterprise oriented and adopted by research institutions should be established. R&D should be encouraged, and special funds should be set up for the three new products. These funds should be

directly allocated to enterprises such that their capacity for innovation and sense of responsibility are stimulated. The three new products must also be included in the *National Agricultural Science and Technology Support Plan*. As for enterprises, they should develop new products that are technically reliable, highly adaptable, easily transportable, and reasonably priced to build a solid foundation for the industrialization and commercialization of the PBD industry in China.

Complete management system for scientific and technological achievements should be built, intellectual property should be safeguarded, and independent innovation should be supported. The appraisal and award system should be carried out to effectively translate the results of scientific research into productive forces.

5.4. *Intensify the self-regulation of the industry and guide enterprise behavior*

A market entry certification system and production license system should be established to ensure product quality. Enterprises should be required to control product quality and wipe out jerry-built products [66]. The MoA should lead the evaluation of a series of brand names and high-quality products and subsequently release a list of recommended products. CAREI and China Biogas Society are responsible for building a PBD exhibition center to advertise and popularize new quality products and new technologies.

5.5. *Build and disseminate demonstration projects*

High-quality PBDs should be popularized and tested under governmental loan projects. Different pilot types of digesters can be demonstrated in different areas to enhance the market impact of PBDs. The biogas industry serves not only as waste treatment and comprehensive utilization project but also as energy conservation and environmentally friendly project; thus, the government should enlarge the scope of invitations to bid by allocating a portion of government loans to PBD demonstration projects and unify bidding at the national or provincial level.

5.6. *Perfect follow-up service and strengthen the function of biogas service stations*

Biogas service stations play an important role in biogas dissemination. Manufacturers who are responsible for biogas product sales and construction should establish a complete follow-up service system, with the government in charge of supervision and guidance. Special funds for follow-up services should be allocated to biogas enterprises. The enterprises should in turn oversee the operation of biogas service stations. In the process, technical staff should be recruited and trained by enterprises with qualified certificates, and the salaries should also be paid by the enterprises. These actions will help realize the purpose of supplying long-term reliable services to users. The training of technical staff could be incorporated into rural energy occupational skills identification and the “Sunshine Project,” a government-sponsored training program that aims to improve the qualification of employees.

6. Future prospects of PBDs

Since the “Rural Ecological Enrichment Project” was proposed by the MoA, biogas construction projects have been implemented all over China [67]. Consequently, household biogas digesters have undergone explosive growth in terms of the number of installed units and the popularization rate. With smallholder farms gradually decreasing and with large-scale farms becoming very common, increasing attention to and support for the biogas sector are being shifted from household biogas to medium- and large-scale biogas plants. Nevertheless, the number of household biogas digesters is predicted to maintain a steady growth in the next years.

PBDs were developed in China because of the disadvantages of OCDs, including long construction periods, relatively short lifetime, and heavy construction material causing high transport cost. By contrast, PBDs could bear sufficient mechanical strength with good air tightness and long service life because the quality of PBDs is permanently controlled at the factory. PBDs are lightweight and can thus be easily transported.

Mountains cover two-thirds of the total land area in China. In remote mountain areas where modern energy is difficult to access and where the transport of construction materials is difficult, biogas is promoted, and PBD would be a preferential choice.

Some natural factors, such as floods and earthquakes, normally destroy biogas digesters built onsite. If the tightness of OCDs is affected, repairing and restoring them to their normal operational state is difficult. In 2008, the Wenchuan earthquake destroyed infrastructure, including biogas digesters in Sichuan Province. Restoring OCDs in their original state under a short period to meet the energy demand of rural reconstruction areas was nearly impossible. Therefore, the Sichuan Rural Energy Office introduced PBDs and made the digesters immediately functional. Currently, Sichuan Province leads in the dissemination of PBDs in China, as more funds are allocated by the local government to this province compared with the other regions across the country.

The PBD market has begun to take shape with an annual capacity of 500,000 to 1,000,000 sets. Old OCDs are quickly being replaced by PBDs to take full advantage of the benefits of biogas. At present, only one industrial PBD standard for FRP digesters is in place. However, the China Association of Rural Energy Industry and other organizations are contributing to the drafting of standards for other PBDs such as PS and PH digesters. New PBD standards will be issued to guide the promotion of PBDs in China.

Other countries implementing national biogas programs, such as Nepal, Bangladesh, Vietnam, and Myanmar, are also testing PBDs. The initial models are mostly imported from China, as factory production of PBDs is nonexistent in other developing countries, and the quality of locally produced PBDs is relatively low. As mentioned in Section 2, international cooperation could bring new markets to the Chinese PBD industry.

7. Conclusion and outlook

With the development of the Chinese biogas industry in the past few years, the PBD industry has begun to emerge. The development of the PBD industry in China, particularly the barriers and challenges as well as the potential actions to be undertaken, is discussed in this paper. Compared with that of traditional OCDs, the market share of PBDs is still small, but their market potential is huge. However, the development of the PBD industry in China is still at its infancy. Therefore, this paper also analyzes and emphasizes existing barriers and challenges, including inappropriate standardization system, lack of demonstration projects, impact of low-quality products, and lagging authorization by the inspection department. To address these issues, preferential policy should be formulated in favor of this young industry. The industrial standardization system should be improved, technological innovation should be promoted, and the self-regulation of industrial stakeholders should be intensified. Demonstration projects should also be initiated, and follow-up services for users should be improved.

Considering the advantages of PBDs over OCDs, the PBD industry in China has a promising future once barriers are overcome.

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